Trajectory Simulation of Meteors Assuming Mass Loss and Fragmentation

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Introduction and Objective

TRAJ **Features:**

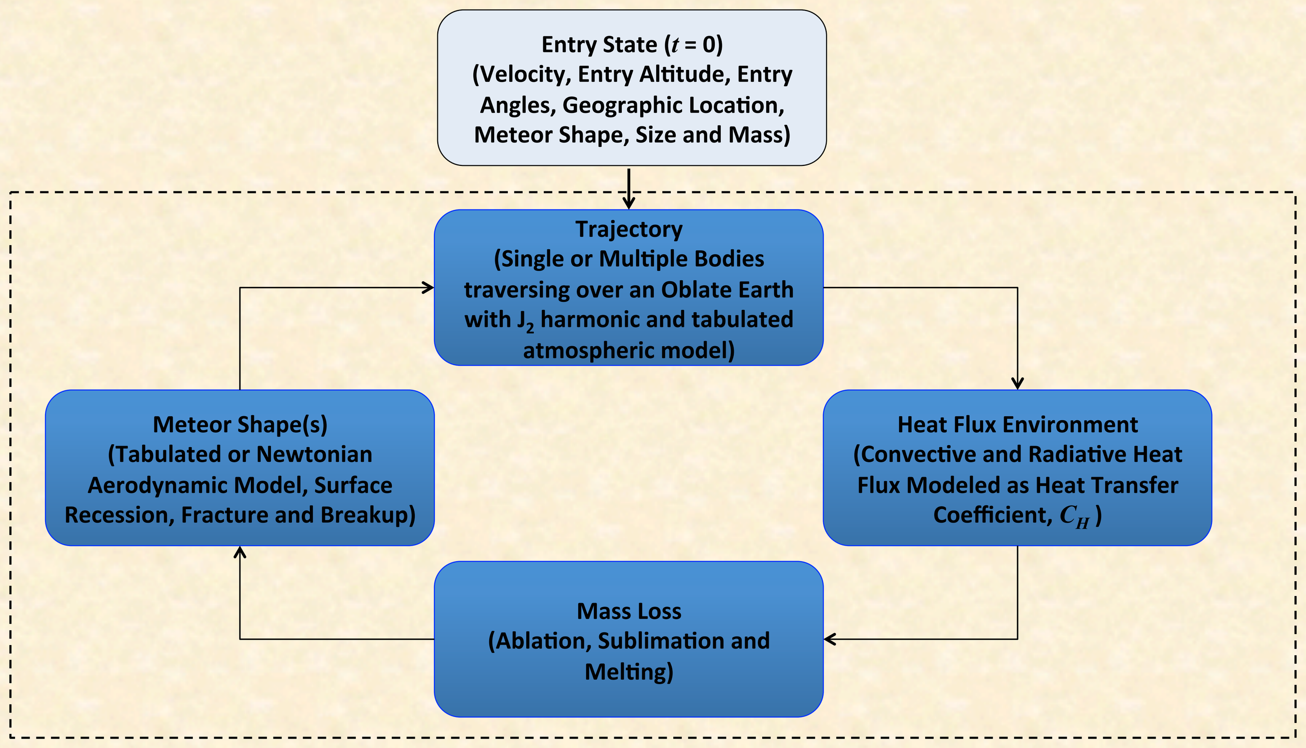
- Program used to simulate atmospheric flight trajectories of entry capsules [1]
- Includes models of atmospheres of different planetary destinations – Earth, Mars, Venus, Jupiter, Saturn, Uranus, Titan, …
- Solves 3-degrees of freedom (3DoF) equations for a single body treated as a point mass
- Also supports 6-DoF trajectory simulation and Monte Carlo analyses
- Uses Fehlberg-Runge-Kutta (4^{th}–5^{th} order) time integration with automatic step size control
- Includes rotating spheroidal planet with gravitational field having a J_2 harmonic
- Includes a variety of engineering aerodynamic and heat flux models
- Capable of specifying events – heatshield jettison, parachute deployment, etc. – at predefined altitudes or Mach number
- Has material thermal response models of typical aerospace materials integrated

Modify trajectory simulation tool, *TRAJ*, to make it suitable for meteor entries including mass loss & fragmentation

Modifications Made to *TRAJ* for Meteor Simulation

- NASA's Galileo probe to Jupiter only one that experienced significant mass loss
- Entry capsule was a 45° sphere-cone with fully-dense carbon phenolic as heatshield material
- M. Tauber *et al.* [2] developed *JAE* code for simulation of Galileo probe (Jupiter entry)
- *JAE* logic incorporated into *Traj*
  - Sphere-cone shape replaced by sphere
  - Mass loss equation of meteor physics used
  - Allow input specification of heat of ablation, Q
  - Allow heat transfer coefficient to vary in time
  - Time-varying heat transfer coefficients from detailed flow computations curve fit as a function of altitude, velocity, and size

Trajectory Simulation Process with Meteor Physics Equations



Mass Change Equation

$$\frac{dm_m}{dt} = -\frac{1}{2}\rho_a u_m^3 \frac{C_H A_m}{Q}$$

t = Time
A_0 = Cross sectional area at entry
m_m = Mass at time t
u_m = Relative velocity at time t
ρ_a = Atmospheric density time t
Q = Heat of ablation
C_H = Heat transfer coefficient

Shape Change Equation (assuming spherical meteor)

$$\frac{A_m}{A_0} = \left(\frac{m_m}{m_0}\right)^{2/3}$$

Test Case: Chelyabinsk [3]

Basic Assumptions:

Hyperbolic excess velocity:	15.0 km/s
Altitude at entry:	95.0 km
Relative velocity at entry:	19.0 km/s
Relative entry angle:	-18.5 deg
Relative heading angle:	-76.6 deg
Geographic latitude at entry:	54.5 deg

Oblate rotating Earth
Gravitational model includes J_2 term
US-1976 atmospheric model

Meteoroid Assumptions:

Shape:	Sphere
Density of meteoric material:	3300 kg/m^3
Aerodynamic model:	Sphere

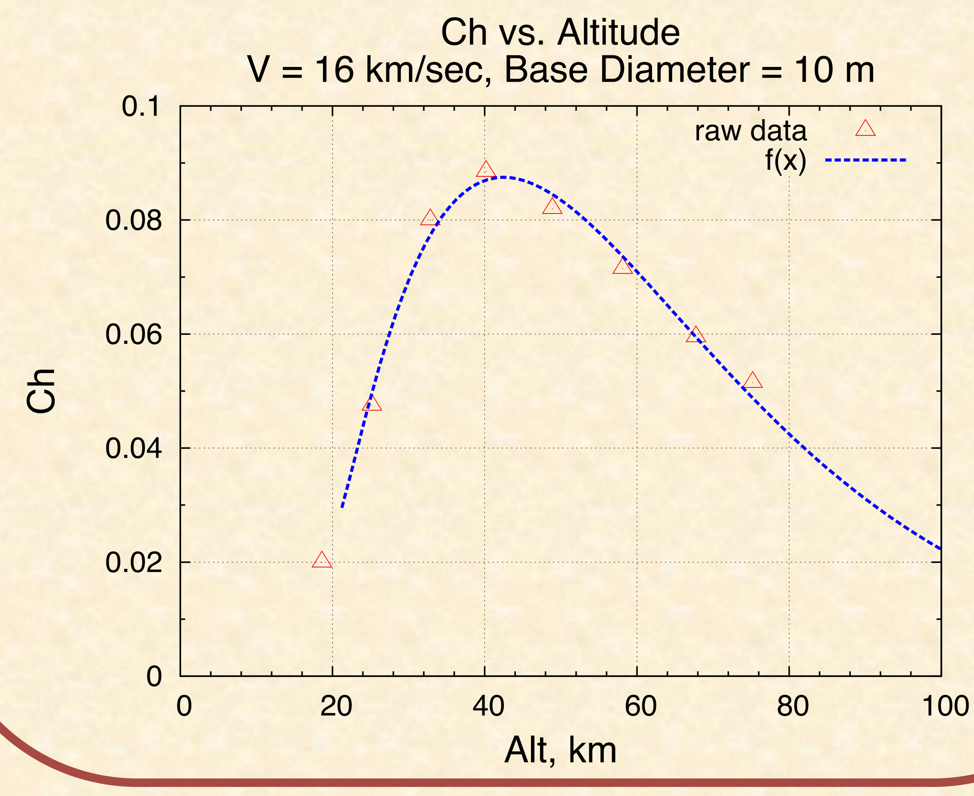
Sensitivity study to entry mass, heat transfer coefficient, heat of ablation, and fragmentation

Heat Transfer Coefficient, C_H, Model

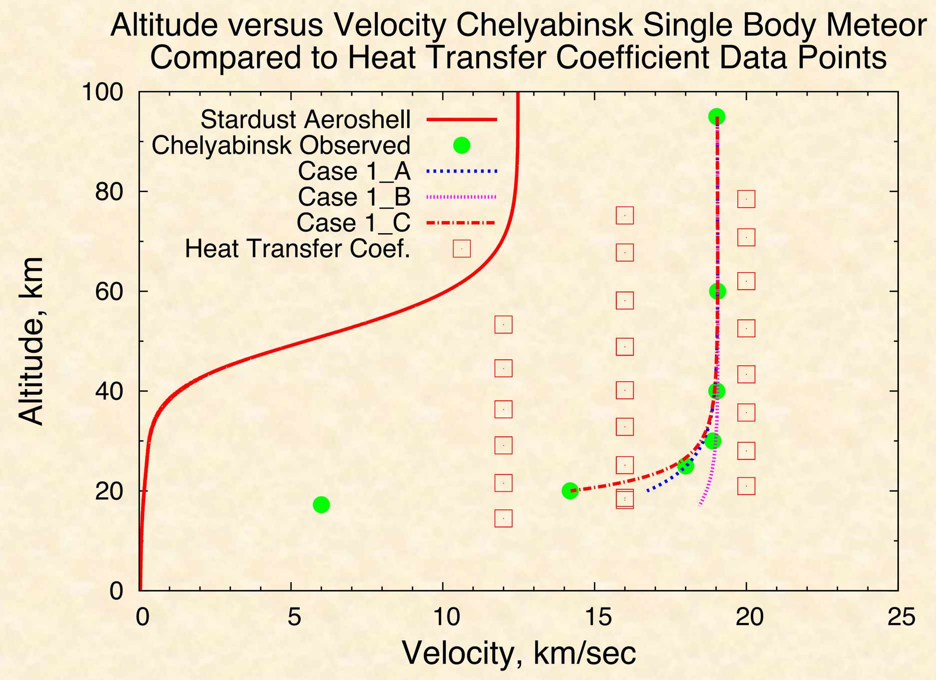
$$C_H(z) = \left[a + b(z-c)^d\right] \exp\left(-\frac{z-c}{f}\right)$$

- Curve fit expressions are to be used for z > 15. 5 km
- C_H for different velocities and diameters obtained through linear interpolation

An example "quality of fit" plot generated with curve fit .



Sensitivity to Basic Assumptions: Entry Mass, Fragmentation, Heat Transfer Coefficient and Heat-of-Ablation

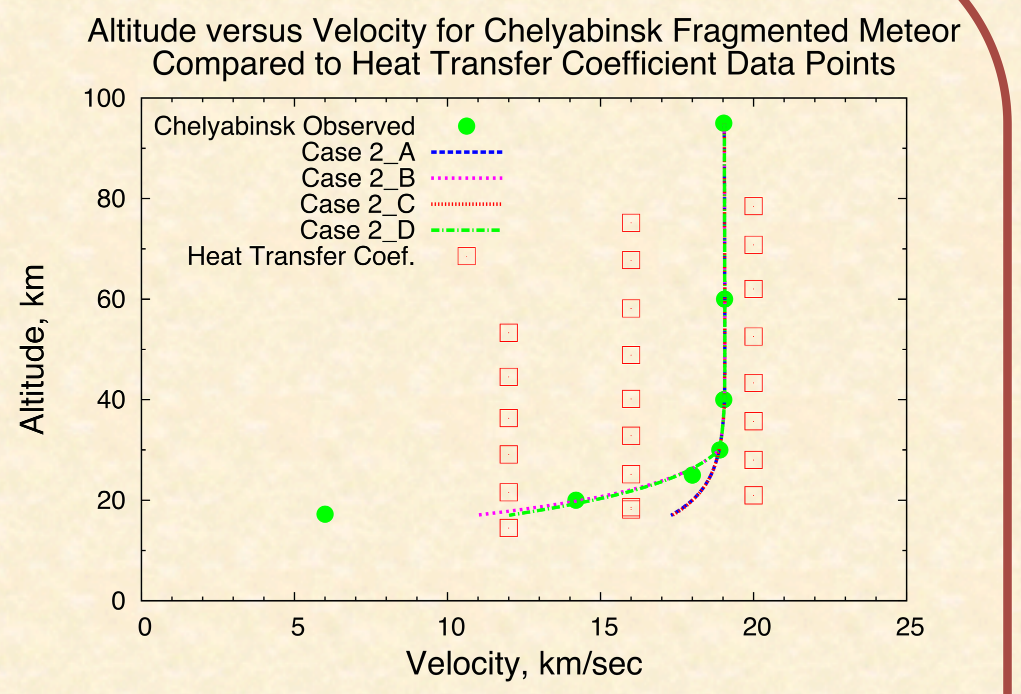


Case 1_A: Single body with C_H = 0.1
Case 1_B: Single body with time varying C_H

Entry mass:	13 x10^6 kg
Meteor radius at entry:	9.8 m
Heat-of-Ablation:	8 MJ/kg

Case 1_C: Time varying C_H for a single body. Entry mass and heat of ablation tuned to overlay Chelyabinsk observations

Entry mass:	6.8 x10^4 kg
Meteor radius at entry:	1.7 m
Heat-of-Ablation:	0.85 MJ/kg



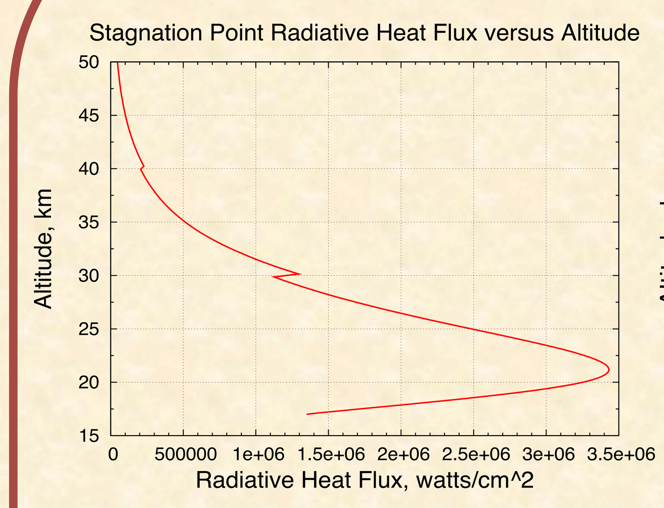
Case 2_A: Single fragmentation event at 40 km, and C_H = 0.1
Case 2_B: Two fragmentation events at 40 & 30 km, and C_H = 0.1
Case 2_C: Single fragmentation event at 40 km, and C_H time varying
Case 2_D: Two fragmentation events at 40 and 30 km, and C_H time varying

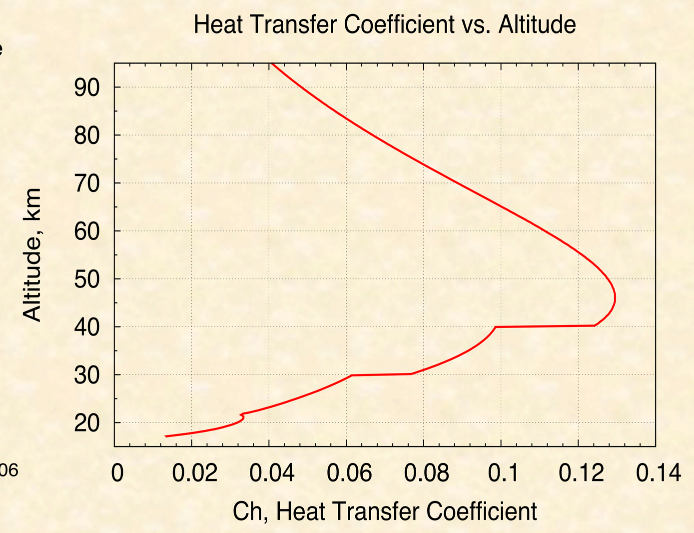
For Cases 2_A – 2_D: Meteor radius: 3.5 m at 40 km alt. Revised mass: 5.93 x10^5 kg

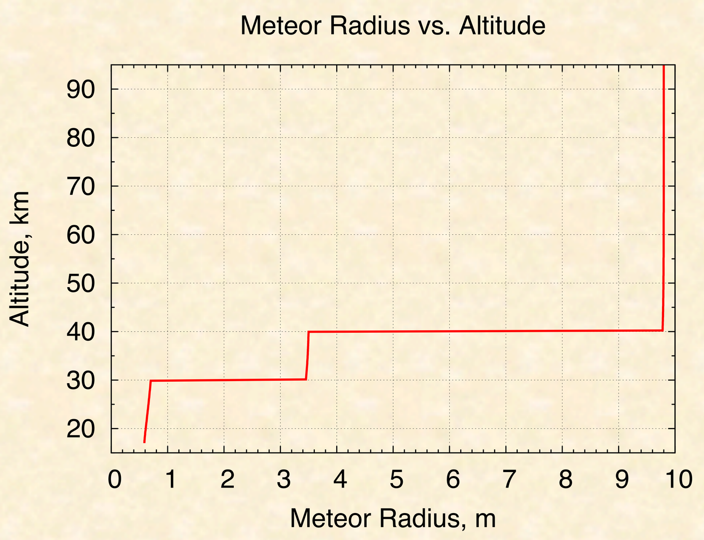
For Cases 2_B & 2_D: Meteor radius: 0.7 m at 30 km alt. Revised mass: 4.74 x10^3 kg

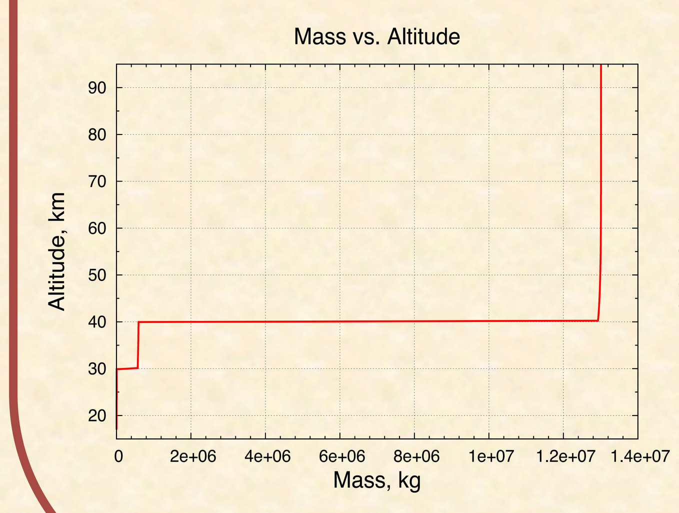
- Myriad ways to fit observations by choice of model parameters and fragmentation events
- Problem compounded by the fact that exo-atmospheric dynamical mass not known precisely

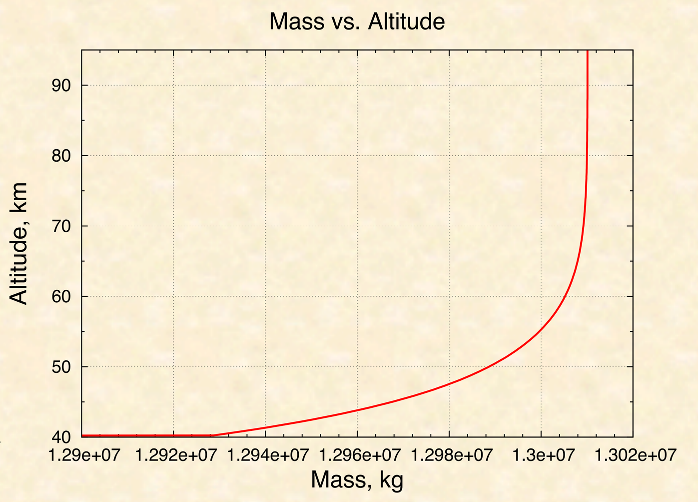
Basic Plots for Variable C_H and Double Fragmentation (Case 2_D)











- For Case 2_D simulation fragmentation at 40 & 30 km altitudes assumed to occur instantly
- Fragment masses tuned to overlay simulated trajectory on Chelyabinsk observations.
- On a scale of 40 to 90 km altitude, mass *vs* altitude trace appears to be a straight line over the entire mass range
- Trace is actually parabolic when mass scale is expanded
- Influence of C_H model is insignificant if large changes occur in meteor mass due to fragmentation.

Conclusions, Future Work and References

- *TRAJ*, an established trajectory simulation tool successfully modified for meteor entries
- Improvements include:
  - Simple mass loss equation of meteor physics
  - Time-varying heat transfer coefficient based on detailed flow computations
  - Ability to specify fragmentation events
- Updated version of *TRAJ* tested against Chelyabinsk observations
- *TRAJ* can now be used to establish sensitivity of trajectories to various meteor parameters
- Leaves open the issue of verification/validation of *TRAJ* and additional test cases are needed
- Could tektites [4] be used as additional test cases?
- Advantages of simulating tektite entries into Earth's atmosphere
  - Exo-atmospheric shapes are definitely spherical
  - Small sizes and (sub)orbital entry velocities
  - Problem is dominated by convective heating and melting
  - Melted shapes are aerodynamically stable
  - Chemical composition of australite tektites is statistically well defined
  - Serve as a good foundation for the tougher meteor entry problem

Recovered australite tektite

References:

1. Gary A. Allen, Jr., Michael J. Wright, and Peter Gage, "The Trajectory Program (Traj): Reference Manual and User's Guide," NASA TM-2004-212847, 2005.
2. Michael E. Tauber, Paul Wercinski, Lily Yang, and Yih-Kanq Chen, "A Fast Code for Jupiter Atmospheric Entry Analysis," NASA/TM-1999-208796, September 1999.
3. Jiri Borovicka, *et al.*, "The trajectory, structure and origin of the Chelyabinsk asteroidal impactor," *Nature,* **503**, 235-237, 14 November 2013.
4. George Baker, "Structures of Well Preserved Australite Buttons from Port Campbell, Victoria, Australia," *Meteoritics,* **3**(4), December 1967.

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